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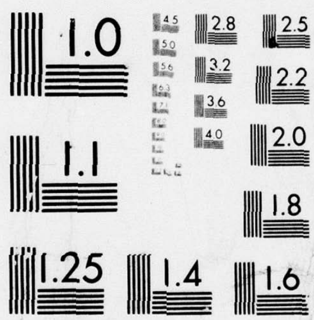

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MEMORANDUM REPORT NO. 2752

(Supersedes IMR No. 447)

RESPONSE OF THREE TYPES OF TRANSIENT COMBUSTION MODELS TO GUN PRESSURIZATION

Carl W. Nelson

May 1977

USA ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
USA BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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Three types of models for transient solid propellant combustion are applied under an imposed pressure history of a 105mm tank gun. The three types are: (1) dp/dt dependence, (2) Quasi Steady Heat Feedback One Dimensional (QSHOD), and (3) Zeldovich. Each predicts a qualitatively different response for the same propellant thermal and thermodynamic properties under the same imposed pressure history.

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LIST OF SYMBOLS

A	pre-exponential constant for surface reaction (non-dim)
C_p	specific heat of gas
C_s	specific heat of solid
E	activation energy for surface reaction (non-dim)
H	heat feedback parameter (portion coming from exothermic pyrolysis)
m	burning rate parameter in KTSS model
n	burning rate pressure exponent
P	pressure
P_o	reference pressure
R	non-dimensional burning rate
r_o	steady state burning rate
T	temperature
T_o	initial propellant temperature
T_s	surface temperature
T_{so}	reference surface temperature
x	distance
z	pressure exponent in Kooker model
α	thermal diffusivity
Ω	constant in Kooker model
σ_p	temperature sensitivity of burning rate
Θ_s	non-dimensional surface temperature
ψ	a constant coefficient

I. INTRODUCTION

Modeling the ignition and early combustion of a solid propellant granular bed has typically assumed that, once ignited, the regression rate depends only on the instantaneous gas pressure (usually $r=aP^n$). For lumped parameter gun codes, like Baer-Frankle[1], it has been the practice to adjust the two parameters (a, n) in the burning rate expression to induce an agreement between measured gun pressures and computed pressures. Such an adjustment process permits the burning rate to compensate to some degree for other errors in input data. Although the adjustments do permit parametric studies of gun performance, the disagreement with independent burning rate measurements prohibit the usefulness of the burning rate formula for any other gun.

Within the past five years, there have been several one-dimensional models of the flame spreading and combustion of the granular propellant bed. All these models use the same power law burning rate formulation as the lumped parameter models ($r=aP^n$). Until recently no serious consideration has been given to using other laws for burning rates probably because either no definitive solutions are available for the burning rate and/or the approximate models require too much additional computing. To date there have not even been approximations used to find a model's sensitivity to potential transient burning effects.

Considerable work has been directed to transient combustion of solid propellants in rocket motors. Emphasis has been on linear or nearly linear perturbations in chamber pressure oscillation or in extinguishment by depressurization. Kooker and Zinn[2] did a numerical investigation of the transient burning coupled to a solid rocket motor chamber by a nonlinear method and predicted some sharp burning rate transients with only small amplitude pressure oscillations. Recent work by Caveny et al[3] attempted to model transient burning in gun conditions by using an approach due to Zeldovich for transient heat feedback to the propellant surface. Nonlinear models of the combustion

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[1] *P. G. Baer and J. M. Frankle, "The Simulation of Interior Ballistic Performance of Guns by Digital Computer Program", BRL Report No. 1183, December 1962 (AD #299980).*

[2] *D. E. Kooker and B. T. Zinn, "Numerical Investigation of Non-Linear Axial Instabilities in Solid Rocket Motors", BRL Contract Report No. 141, March 1974 (AD #776954).*

[3] *L. H. Caveny, M. Summerfield, and C. W. Nelson, "Ignition Transients and Pressurization in Closed Chambers", 11th JANNAF Combustion Meeting, Pasadena, CA, CPIA Pub. 261, September 1974.*

were developed by Krier et al[4] and by Levine and Culick[5]. When Kooker and Nelson[6] compared the predictions of the KTSS, Levine, and Kooker models in a typical gun pressure environment, they predicted that three models had the same qualitative response of a single sharp transient at a low pressure and an asymptotic approach to the power law representation as pressure increased.

It is the purpose of this brief report to compare the burning rate predictions of three different types of models for an imposed pressure history found in a typical Army gun.

II. MODELS

$\frac{dp}{dt}$ Dependence Models

Early approximations for the dynamic response were proposed by Paul et al[7], Parker and Summerfield[8] and vonElbe[9]. With some simplified analyses these researchers all arrived at a form for instantaneous burning rate:

$$r = r_o[1 + \psi\frac{n\alpha}{pr_o^2}\frac{dp}{dt}],$$

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[4] *H. Krier, J. S. Tien, W. A. Sirignano, and M. Summerfield, "Nonsteady Burning Phenomena of Solid Propellants: Theory and Experiments" AIAAJ Vol. 6, No. 2, pp 278-285, February 1968.*

[5] *J. N. Levine and F. E. C. Culick, "Nonlinear Analysis of Solid Rocket Combustion Instability", AFRPL TR-74-45, October 1974.*

[6] *D. E. Kooker and C. W. Nelson, "Numerical Solution of Three Solid Propellant Combustion Models During a Gun Pressure Transient", 12th JANNAF Combustion Meeting, Newport, RI, August 1975.*

[7] *B. E. Paul, R. L. Levine, and L. Y. Fong, "A Ballistic Explanation of the Ignition Pressure Peak", AIAA Solid Propellant Rocket Conference, Palo Alto, CA, AIAA Paper 64-121.*

[8] *K. Parker and M. Summerfield, "The Ignition Transient in Solid Propellant Rocket Motors", Princeton University, Dpt. AMS Report 769, 1966.*

[9] *G. vonElbe, "Solid Propellant Ignition and Response of Combustion to Pressure Transients, AIAA Paper 66-668, 1966.*

where r_o steady state burning rate
ψ a constant coefficient
α thermal diffusivity
n burning rate exponent
P instantaneous pressure
$\frac{dp}{dt}$ time derivative of pressure.

Krier[10] briefly reviewed the derivations and their limitations to small changes from steady state operation. The coefficient ψ is different for each derivation (1/2 for Parker and Summerfield; 1 for Paul et al; 2 for vonElbe). Krier then relaxed the assumption of constant surface temperature and used the KTSS model of dynamic heat feedback to derive a variable expression for ψ:

$$\psi = \frac{\left[1 - \frac{(p/p_o)^{n/m}}{m}\right]}{\left[(p/p_o)^{n/m}(2+1/n)-2H\right]} ,$$

where P_o reference pressure
m a constant
H a non-dimensional surface heat release.

Quasi Steady Heat Feedback One Dimensional (QSHOD)

Three models solve the partial differential energy equation in the solid propellant using a nonlinear boundary condition at the propellant surface. Kooker and Nelson rederived the governing equations in a common coordinate system and compared the solutions for the pressure field in a 105mm tank gun as is the purpose of this report. The models all use a surface boundary condition of the form

$$\left.\frac{d\Theta}{dx}\right|_o = G_1 R + G_2/R ,$$

where $\frac{d\Theta}{dx}$ non dimensional thermal gradient
R non dimensional regression rate,

but differ in the form of the functions G_1 and G_2 and R. Table I gives the differences.

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[10] *H. Krier, "Solid Propellant Burning Rate During a Pressure Transient", Comb Sci Tech Vol 5, pp 69-73, 1972.*

Table I. Heat Feedback Terms

Model	G_1	G_2	R
KTSS	H	$P^{2n}(P^{n/m}-H)$	$\Theta_s^{\ m}$
Kooker/Zinn	$H+(\Theta_s-1)(1-\frac{C_p}{C_s})$	$\Omega^2 \frac{C_p}{C_s}(\frac{T_{so}}{T_{so}-T_o})P$	$\exp[\frac{A(\Theta_s-1)}{1+\frac{A}{E}(\Theta_s-1)}]$
Levine/Culick	$H+(\Theta_s-1)(1-\frac{C_p}{C_s})$	$P^{2n}\{[\frac{C_p}{C_s}\frac{E}{A}(\frac{1}{1-\frac{n}{E}\ln P}-1)]+(1-H)\}$	$\exp[\frac{A(\Theta_s-1)}{1+\frac{A}{E}(\Theta_s-1)}]$

where Θ *non dimensional* temperature
c heat capacity
T_{so} reference surface temperature
A,E non dimensional kinetic constants.

The G_1R term represents heat from the exothermic surface reaction and G_2R represents heat from the flame. Kooker and Nelson found that the Kooker/Zinn and Levine/Culick models gave practically the same response and that the KTSS model predicted higher overshoots because of the presence of the $(\theta_s-1)(1-\frac{C_p}{C_s})$ term in the surface heat release term.

Zeldovich Model

Caveny et al used the Zeldovich approach to derive a nonsteady heat *feedback of the form*

$$\left.\frac{dT}{dx}\right|_o = \frac{R}{\alpha}[T_s-\ln(\frac{R}{R_o})/\sigma_p+T_o] ,$$

where σ_p temperature sensitivity.

The advantage gained is that no model of the flame need be specified. The non-steady heat feedback from the flame at $R(T_o,P)$ is assumed to be the same as the feedback at $R_o(R_{oeq},P)$ when T_{oeq} is the initial temperature which would yield steady burning at $R(P)$. With that boundary condition, the thermal energy equation of the solid propellant is solved numerically.

The Test Case

A reference set of thermal and thermodynamic properties were assigned to a double base propellant. Best estimates from whatever experimental data were available were used. The only parameter which is observed to have a dramatic effect on the results is the value of the surface heat release in the QSHOD model group. Experimental data from Kubota et al[11] establish that the value can range easily from 70 to 100 cal/gm which corresponds to values of the parameter H from 0.58 to 0.83.

Temperature sensitivity for the propellant was measured as .0046/°K. To be consistent with the other parameters including H, a rough estimate of the temperature sensitivity may be obtained from Summerfield et al[12] as 0.0054/°K. One source of the difference is the derivation's assumption that the KTSS flame contribution to the heat feedback is independent of initial temperature. The difference carries no immediate impact because the results are essentially alike for either value.

The imposed pressure profile was that of the 105mm tank gun starting at 6.9 MPa where the propellant is assumed to be burning at steady state.

III. RESULTS AND DISCUSSION

The shapes of the burning rate response of the three types of models are distinctly different. Figure 1 plots the relative burning rate against time in a pressure field which rises almost linearly at an average rate of about 10^5 MPa/sec. For the models using surface heat release, it was assumed to be 96 cal/gm.

---

[11] *N. Kubota, T. J. Ohlemiller, L. H. Caveny, and M. Summerfield, "An Experimental Study of the Site and Mode of Action of Platonizers in Double Base Propellants", AIAA Paper 74-124, January 1974.*

[12] *M. Summerfield, L. H. Caveny, R. A. Battista, N. Kubota, Yu A. Gostinsev, and H. Isoda, "Theory of Dynamic Extinguishment of Solid Propellants with Special Reference to Nonsteady Heat Feedback Law", Journal of Spacecraft Rockets, 8 (3), March 1971, pp 251-258.*

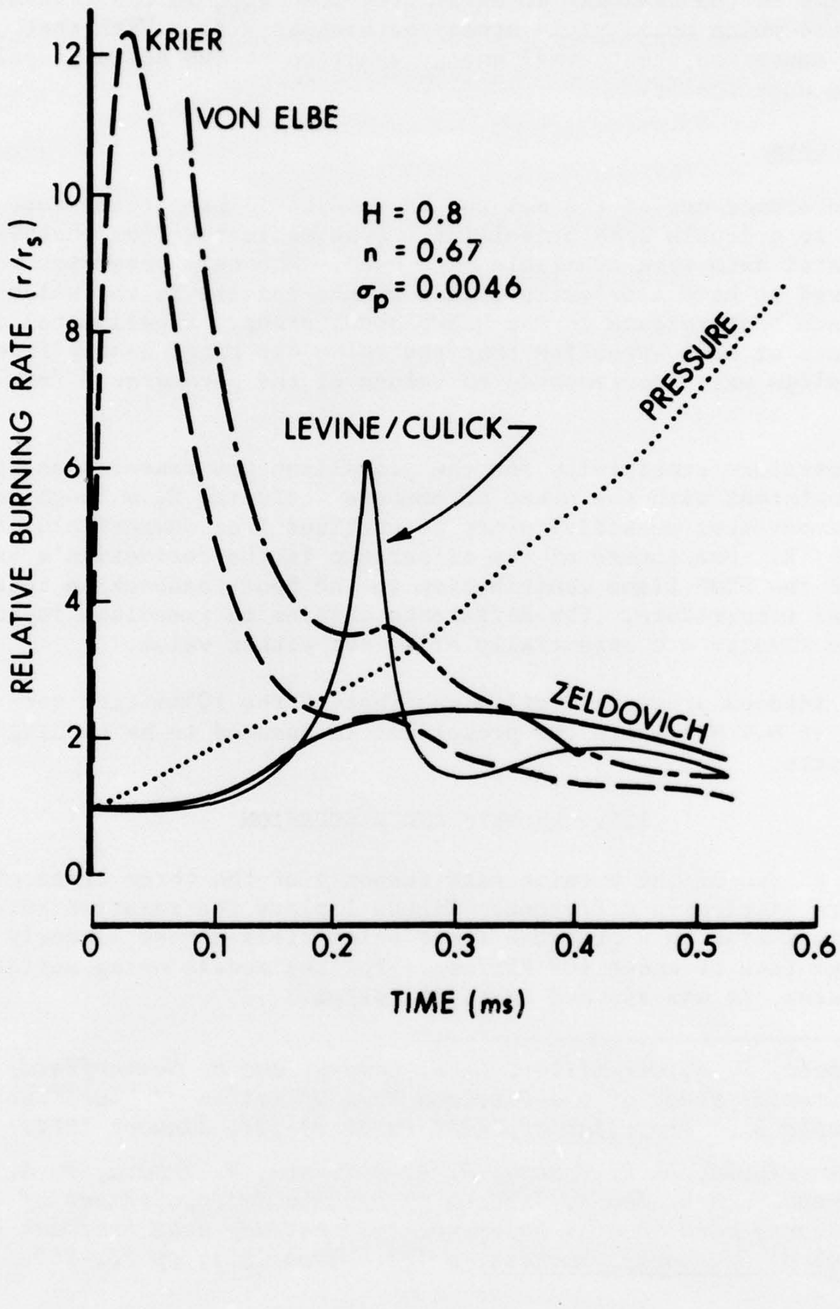

Figure 1. Comparisons of Relative Burning Rates

Two values of ψ in the dp/dt model showed different results, although the same general shape. The Krier version reached a peak of 12.4 when the vonElbe version reached 17.4. The vonElbe curve was consistently higher than the Krier curve throughout the time examined. For the Krier version, the coefficient was initially about 1.5 and declined steadily to 0.7 at 0.5ms.

The QSHOD models all had the same shape which produced a sharp peak at 0.25ms. Peaks for the Levine/Culick and Kooker/Zinn were about the same at 6.1 but the KTSS peak was much higher at about 17 (not shown in Figure 1). Kooker and Nelson provide a more complete comparison for this type model.

For the Zeldovich model a much lower response was observed. The peak overshoot of only 2.1 occurred at 0.4ms.

In the computations, burning rate excursions did not affect the imposed pressure. In an actual chamber the two would be coupled because the faster gas generation rate would increase the pressurization rate. The mass of gas in the chamber is proportional to the integral $\int_o^t r dt$. To the extent that this integral exceeds the quasi-steady integral $\int_o^t r_o dt$, the chamber pressurization will be altered by the burning rate excursions. A rough estimate of the effect is given in Table II where the ratio $\int r dt / \int r_o dt$ is compared at different times. Translating the ratios into real chamber effects would require a coupling to the chamber dynamics.

Experimental verification of the magnitude of such burning rate excursion has not been made. Closed vessel tests of granular beds typically discard the low pressure information because of uncertainties in surface area and ignition spreading. Sharp spikes have been only occasionally reported and usually ignored as a test anomally. An inference to be drawn is either the spikes do not occur or the time for flame spreading is of the same order as the time for the burning rate excursion. Resolution awaits better experimental information.

Table II. Gas Production Ratios

	0.1ms	0.25ms	0.5ms	0.8ms
dp/dt ψ = 2	13.1	7.10	3.91	2.47
dp/dt ψ = f(p)	9.0	4.75	2.64	1.79
Levine/Culick	0.97	2.16	1.81	1.52
Zeldovich	0.97	1.21	1.43	1.40

A serious criticism may be leveled at applying the QSHOD models to nitrocellulose based gun propellants. The derivation of the flame contribution to the heat feedback assumes a uniform distribution of the energy release in the flame on the basis that composite propellant flames are diffusion controlled. Because nitrocellulose based propellants are avidly believed to have premixed, kinetically controlled, thin flames, the models must be reexamined to judge the effect of changing the flame structure. A quick calculation for a flame sheet approximation showed the overshoots to be more like the Zeldovich results. The true energy release distribution lies probably somewhere in between the two extremes with a reasonable conclusion that no clear case can be made for choosing between the Zeldovich and QSHOD models for a nitrocellulose based propellant.

The implications of this study are not limited to the particular problem chosen. The gun pressure profile selected, monotonic and nearly linear, is not strictly limited to guns. Two real cases can be conceived where the results are applicable: A gun with a composite propellant, like a nitramine base, or any other vessel like a rocket, with a composite propellant in a rapid pressurization. The message is clear: *do not choose a model on the basis that they all give the same answer.*

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